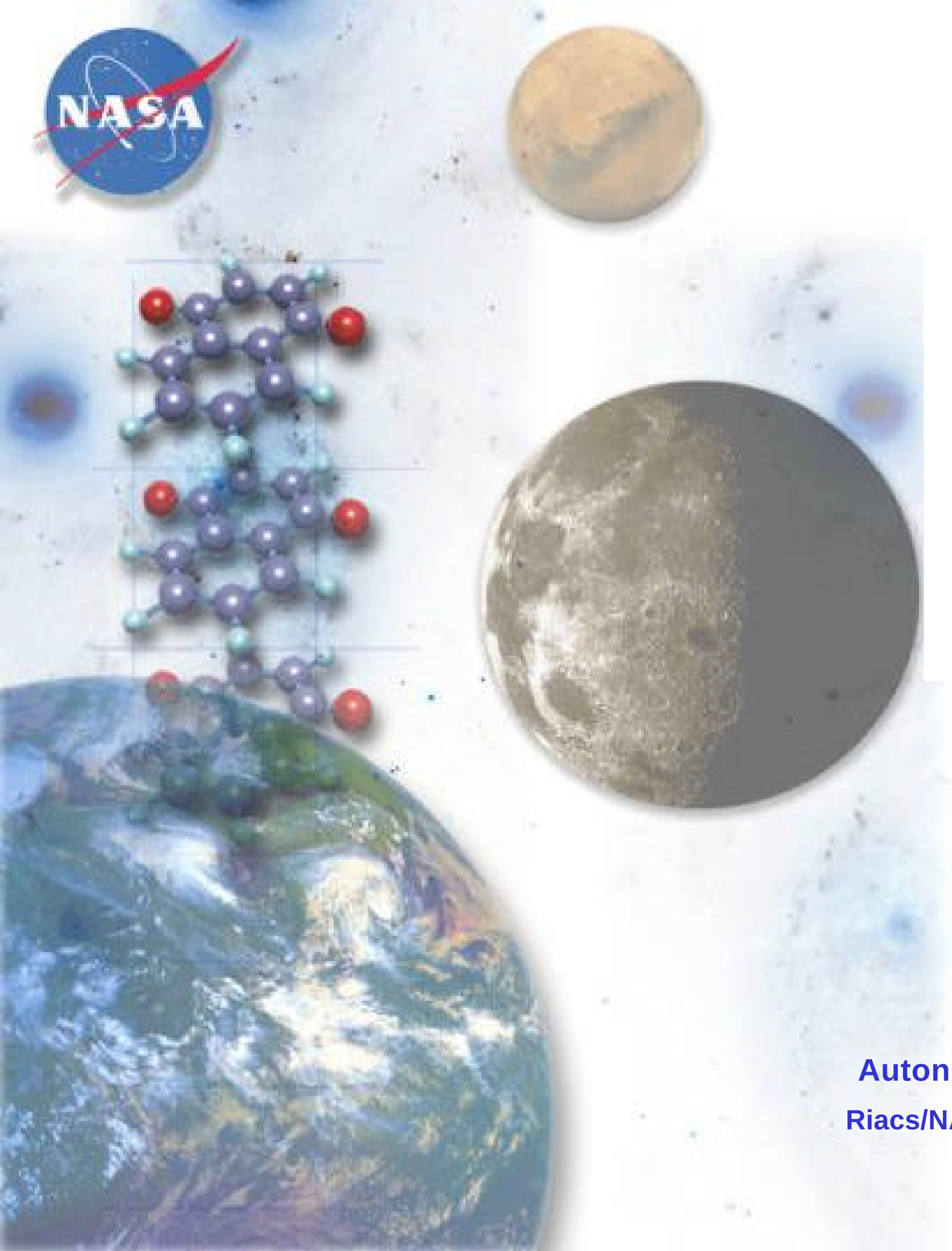


NASA Applications of Autonomy Technology

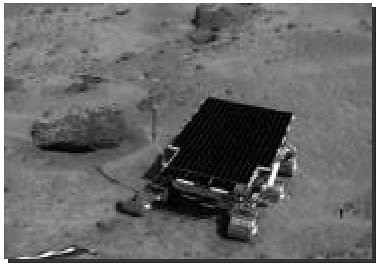
James Crawford

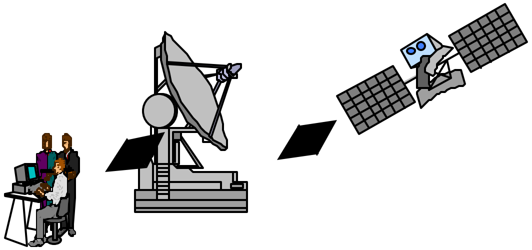
Autonomy and Robotics Area

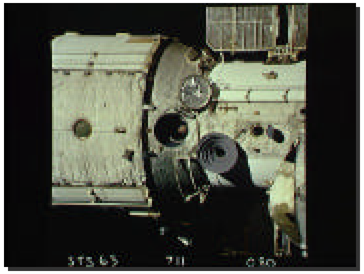
Riacs/NASA Ames Research Center

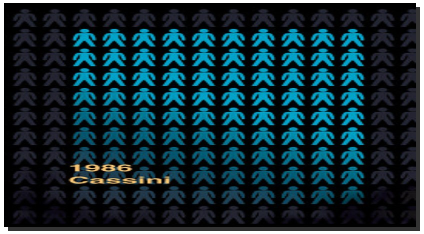
Autonomy Background

- **Robotic explorers spend over 50% of their time awaiting directions to “interesting” features**
  - **“Interesting” determined far away based on downlinked data**
- **Instruments pursue science via uplinked command lists generated by large ground support teams**
  - **Each instrument stands alone, unless coordinated on ground**
- **Cosmonauts spend over 80% of their time maintaining Mir**
  - **Science Program is secondary, worked “as time permits”**
- **Mission flexibility/capability is limited by software development time and resources**



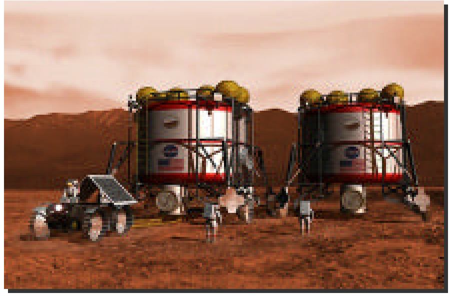




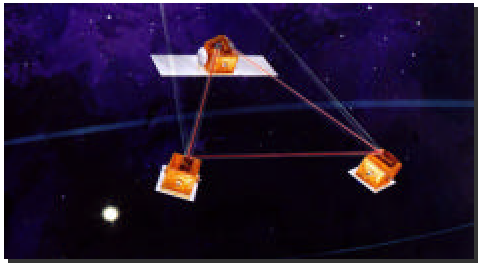


Goals

- **Robotic explorers operating with infrequent human intervention**
  - “Curious” systems which can revise/extend their science program
  - “Wary” systems which can assess/avoid risks

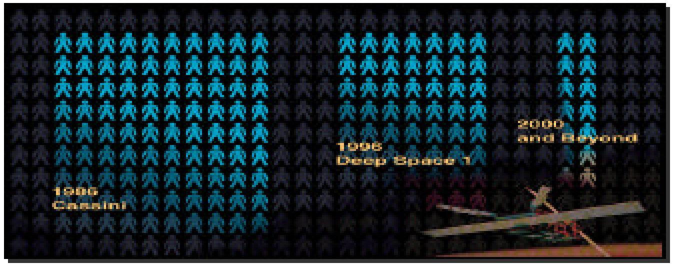


- **Fleets of instruments pursuing collaborative science programs**
  - From low-earth orbit to deep space, and on planetary surfaces
  - Ground based control of individual observations impossible



- **Astronauts pursuing science objectives on the International Space Station with the support of automated systems**
  - Intelligent assistants maximize crew effectiveness, science return

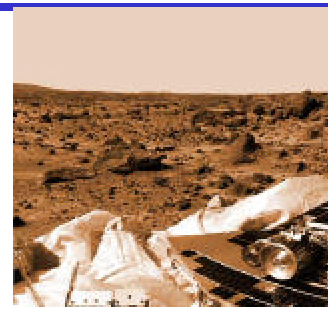
- **Development time for mission software reduced from years to months, while reducing errors by two orders of magnitude**
  - Model-Based paradigm increases flexibility during both development and operations
  - Formal methods increase both speed and coverage of V&V effort

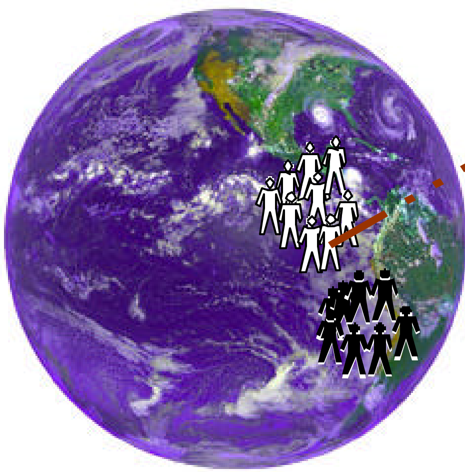


Robotic Exploration of Mars

Sojourner facts

– Max distance from Lander: 12 M
– Total distance traversed 100M
– Time spent waiting: 40-75%
– 2.4 uplinks per science target
– Science cut in half during extended mission





MER – Facts

- *It takes the MER rover a day to do what a field geologist can do in about 45 seconds.* -- Steve Squyres MER 2003 PI
- Amortized cost of MER is $4 to 4.5 M per day of operation. (90 day mission)
- 240 co-located ground support scientists and engineers

MSL Challenges

- Science Definition Team report considered Autonomy enabling to meet baseline mission requirements.
- Mission Duration 1000 days. (for nuclear option)
- Total traverse potential 30km

What is Autonomy?

AUTONOMY

A Simple Definition

Definition:

- Describes a system's ability to perform a task without direction from an external source.

Examples:

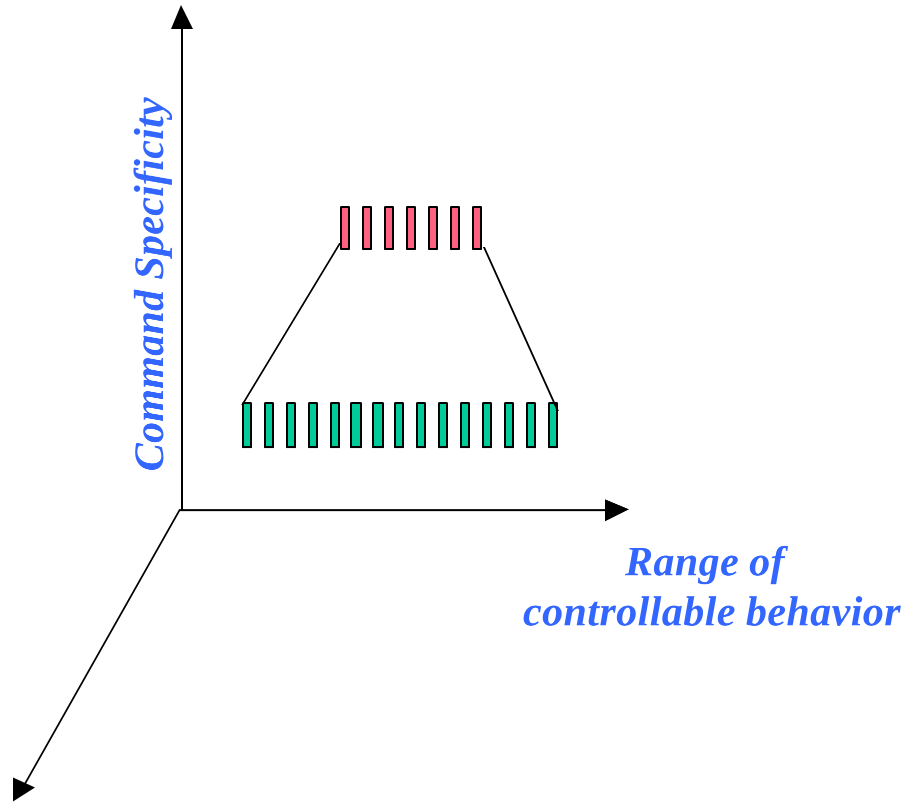
- Train at Disneyworld
- Airplane autopilot
- X-34
- Thermostat (low-level controllers)
- Rock

What do we really mean?

Autonomy describes a systems ability to exhibit *goal directed behavior* by making decisions in response to uncertainties within the external environment, the systems internal health state, and resource availability.

Range of Controllable Behavior:
Range of capabilities that the system can exhibit (control authority).

Command Specificity: Level of abstraction in specification.

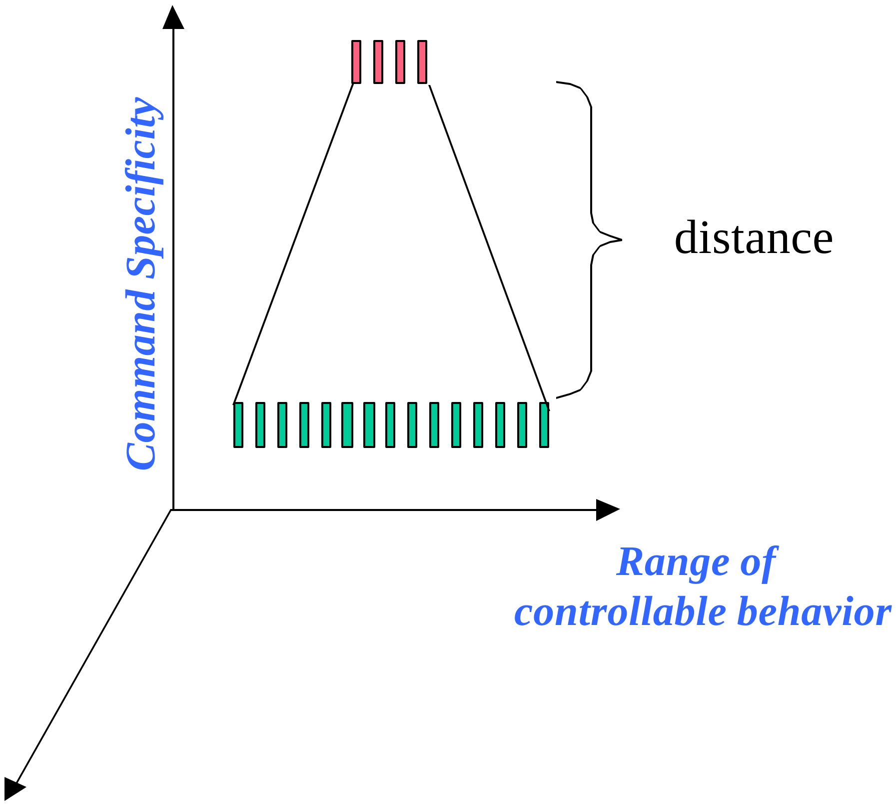


What do we really mean?

Autonomy describes a systems ability to exhibit *goal directed behavior* by making decisions in response to uncertainties within the external environment, the systems internal health state, and resource availability.

Range of Controllable Behavior:
Range of capabilities that the system can exhibit (control authority).

Command Specificity: Level of abstraction in specification.



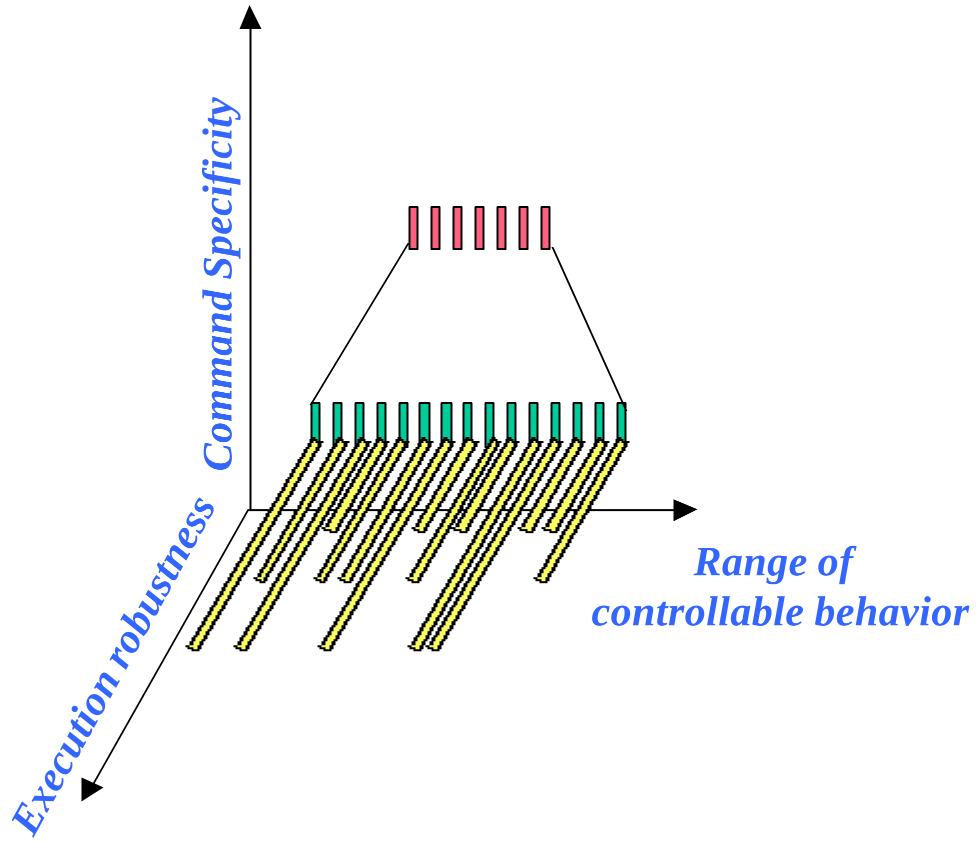
What do we really mean?

Autonomy describes a systems ability to exhibit *goal directed behavior* by making decisions in response to uncertainties within the external environment, the systems internal health state, and resource availability.

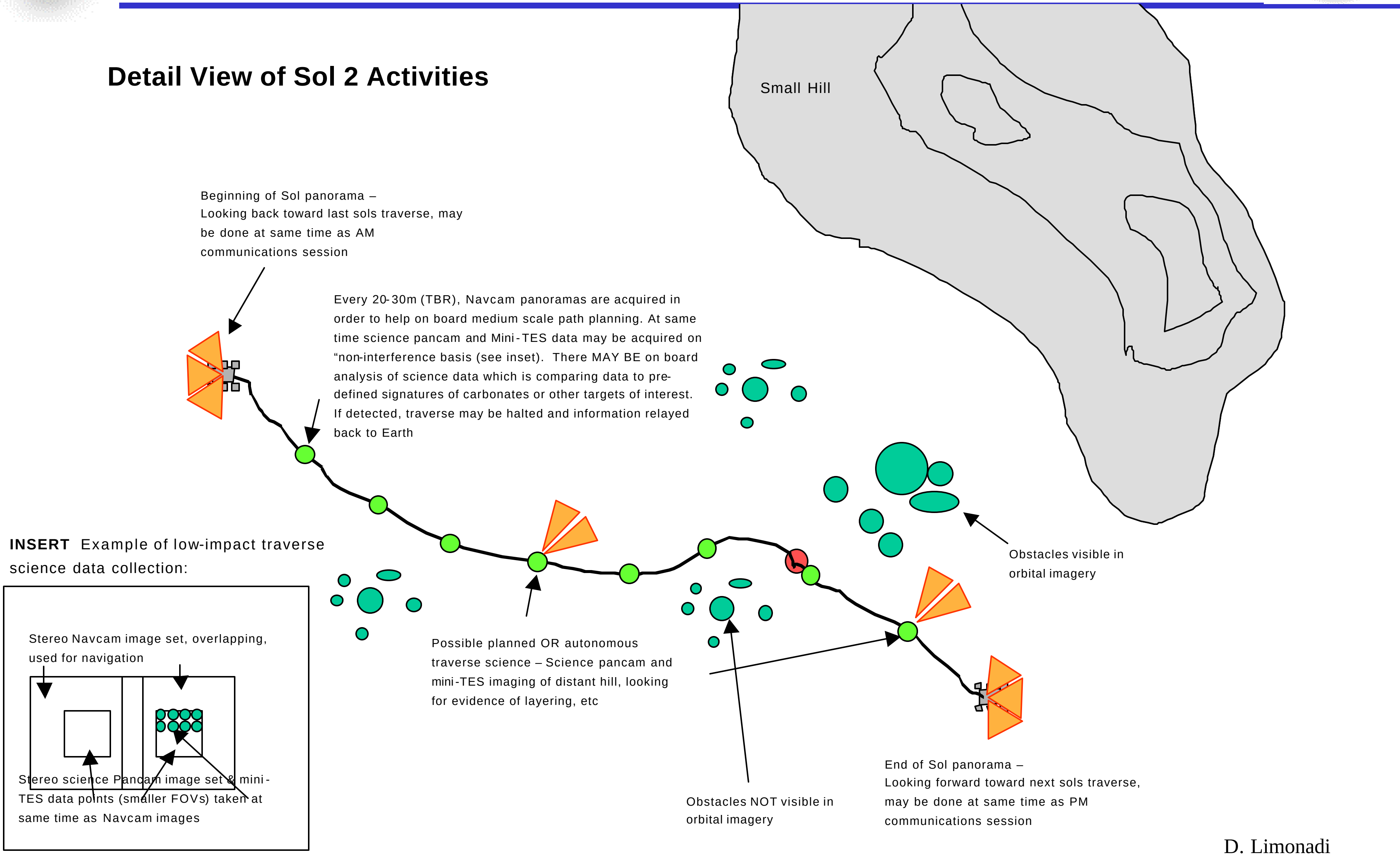
Range of Controllable Behavior:
Range of capabilities that the system can exhibit (control authority).

Command Specificity: Level of abstraction in specification.

Execution Robustness: Envelope of conditions under which system can achieve its goals.



Mission Example – MSL traverse



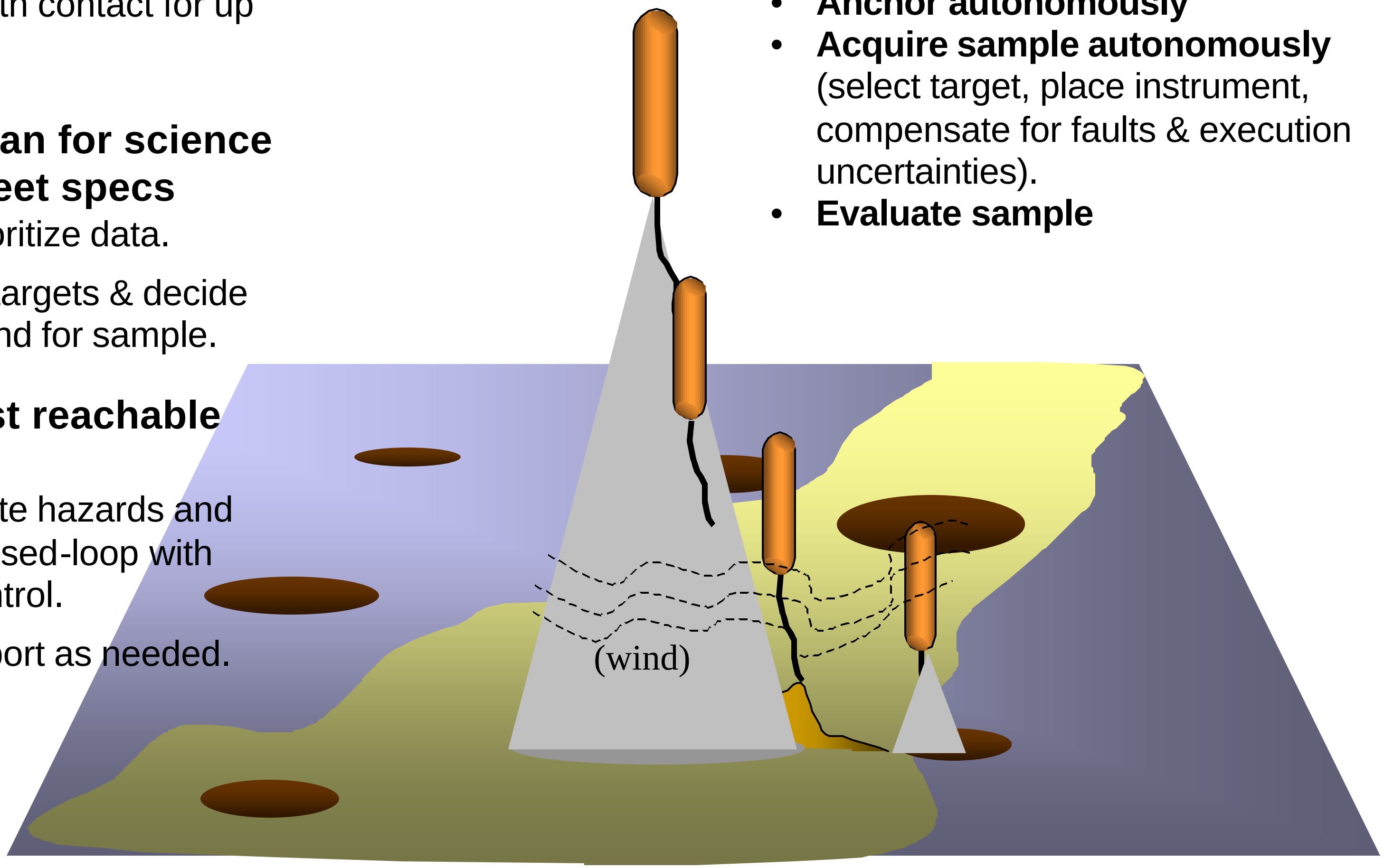
Mission Example – Titan Aerobot

1. Cruise to area of interest
- May be out of earth contact for up to eight days

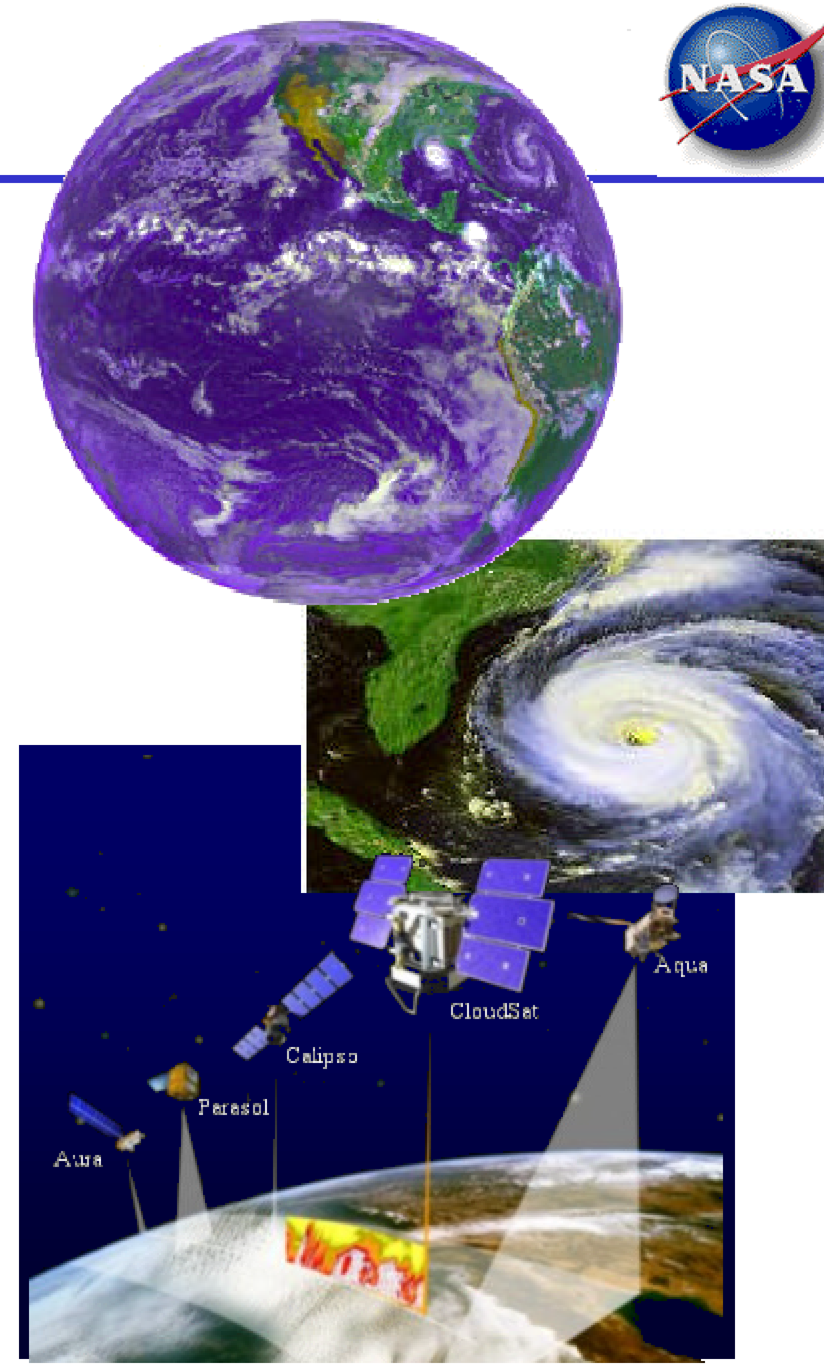
2. Continually scan for science targets that meet specs
- Summarize & prioritize data.
- Identify potential targets & decide whether to descend for sample.

3. Descend to best reachable target
- Continually evaluate hazards and target quality in closed-loop with navigation and control.
- Switch target or abort as needed.

4. Anchor & acquire sample
- **Anchor autonomously**
- **Acquire sample autonomously** (select target, place instrument, compensate for faults & execution uncertainties).
- **Evaluate sample**



Earth Observing



- **Web of interacting platforms**
  - Ground, air, and space
  - Multiple controllable instruments
  - Developed by separate providers
  - Coordinated planning and execution
- **Ability to rapidly respond to phenomenon of interest**
  - Ice pack, storm tracks, fires volcanism, etc.
- **Onboard analysis to overcome bandwidth limitations**
  - Higher resolution cameras
  - Multiple instruments
  - Continuous surveys

Key Points

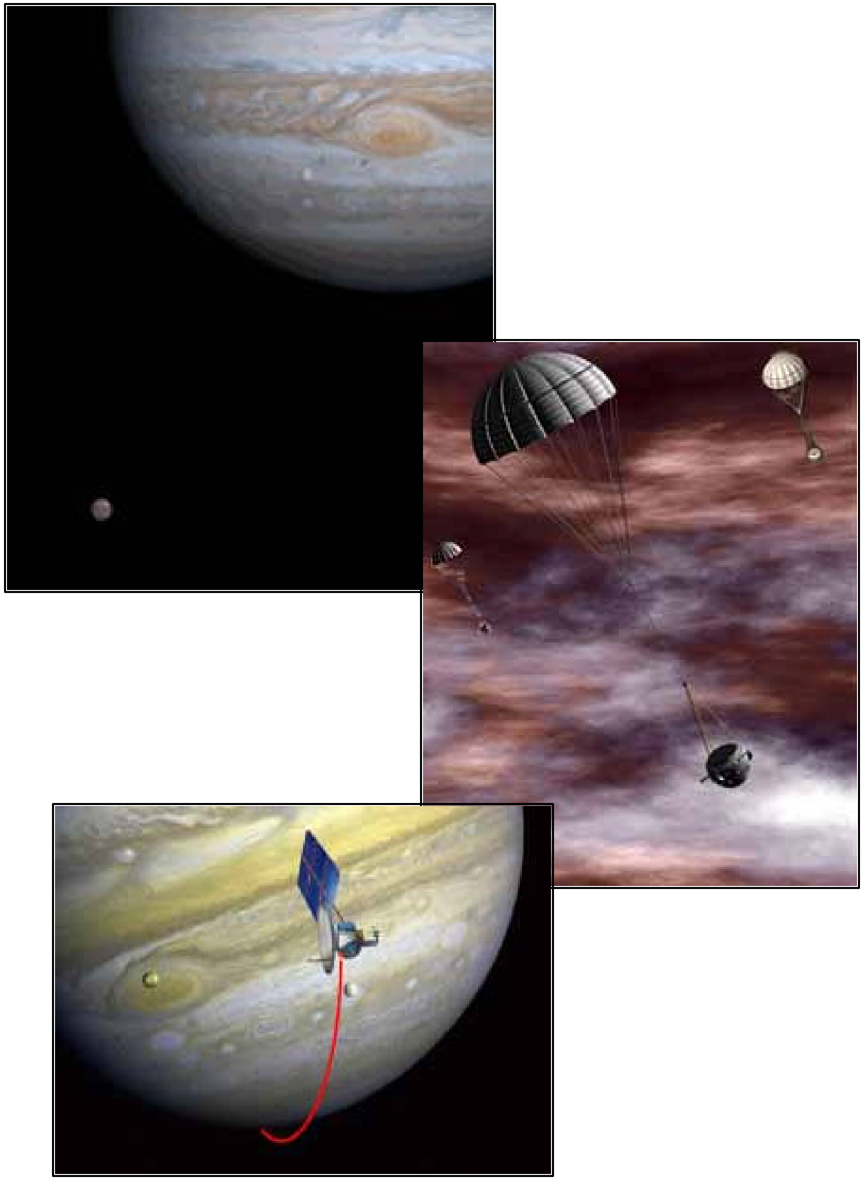
- **Autonomy is a capability, not a technology.**
- **Humans are always in the picture.**
- **Autonomy is nothing new.**
  - **What is new is the *degree* of autonomy and the ability to perform higher-level, cognitive tasks when making decisions.**
- **Don't consider just the device, but rather the entire *system* (i.e. ground, flight, and humans)**
- **Autonomy interacts with data understanding**
  - **Bandwidth limitations**
  - **Rapidly changing situations**

Backup

Jupiter Polar Orbiter with Probes

- **Polar orbiter with three probes to 100 bar**

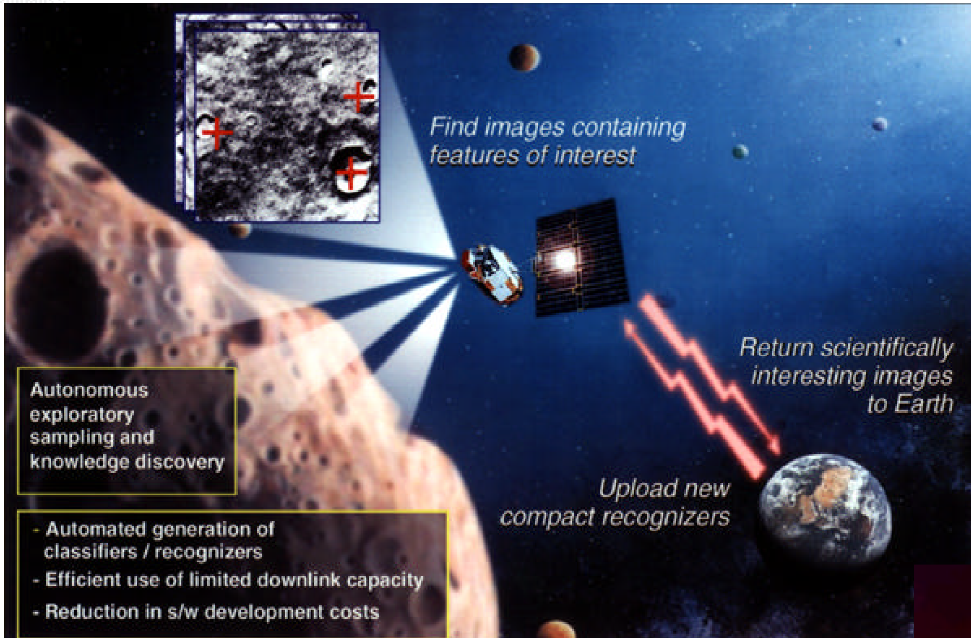
- **Science objectives:**
  - **Probe Jupiter's interior with gravity and magnetic field measurements**
    - "Image" deep atmosphere
    - Detect deep winds
    - Understand internal structure
  - **Measure Jupiter's deep atmospheric composition with multiple entry probes**
    - Measure organics and volatiles
    - Measure wind velocity
    - Cloud opacity and structure



Key technology investment areas

- **Intelligent sensing and reflexive behavior**
- **Planning and execution**
- **Fault protection**
- **Agent architectures and distributed autonomy**

Intelligent Sensing and Reflexive Behavior



Detect science opportunity…

- Solar flare
- Volcanic eruption
- Interesting Mars rock
- Geologic process

… and react

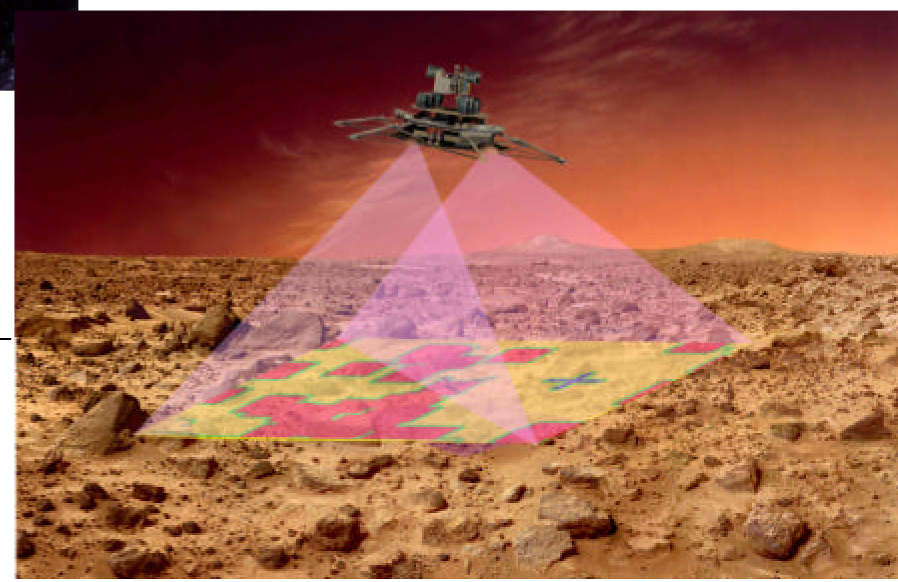
- Generate new plan to observe event
- Downlink "interesting" events

Assess environment …

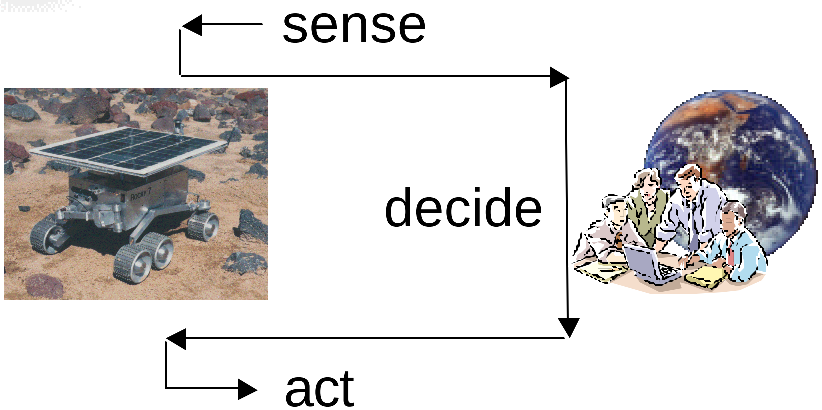
- Estimate position & attitude
- Find safe landing sites
- Find scientifically interesting sites

… and react

- Navigate to site & land safely

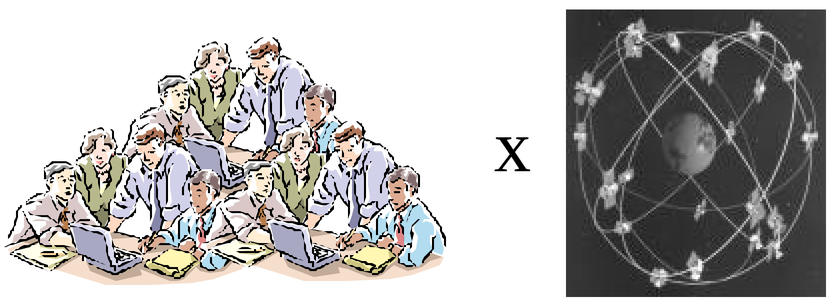


Planning & Execution



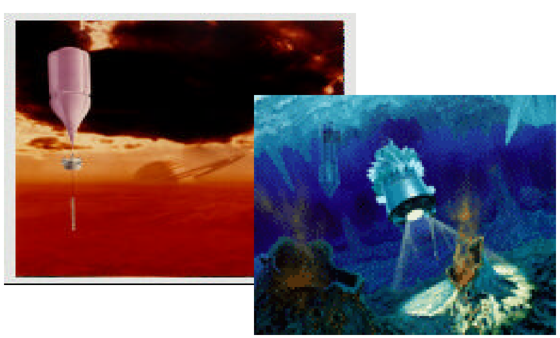
Ground loops devour mission life

- Assets idle while waiting for ground team to assess situation & send new commands
- Assets idle during fault recovery



Ground loops are expensive

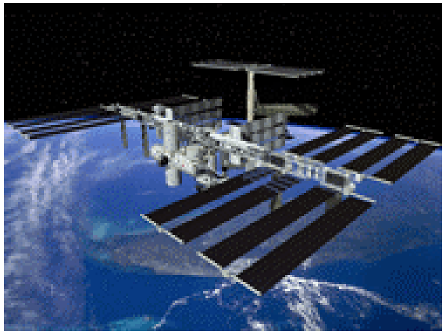
- Ground-based mission planning tools
- Constellations multiply problems



Robust operation in uncertain environments

- Can’t predict needed responses in advance
- Ground-in-the-loop decisions are too slow

Model-based Fault Protection



Key questions:

- Is the system operating nominally? *Monitoring*
- If not, what has gone wrong? *Diagnosis*
- What should I do about it? *Recovery*

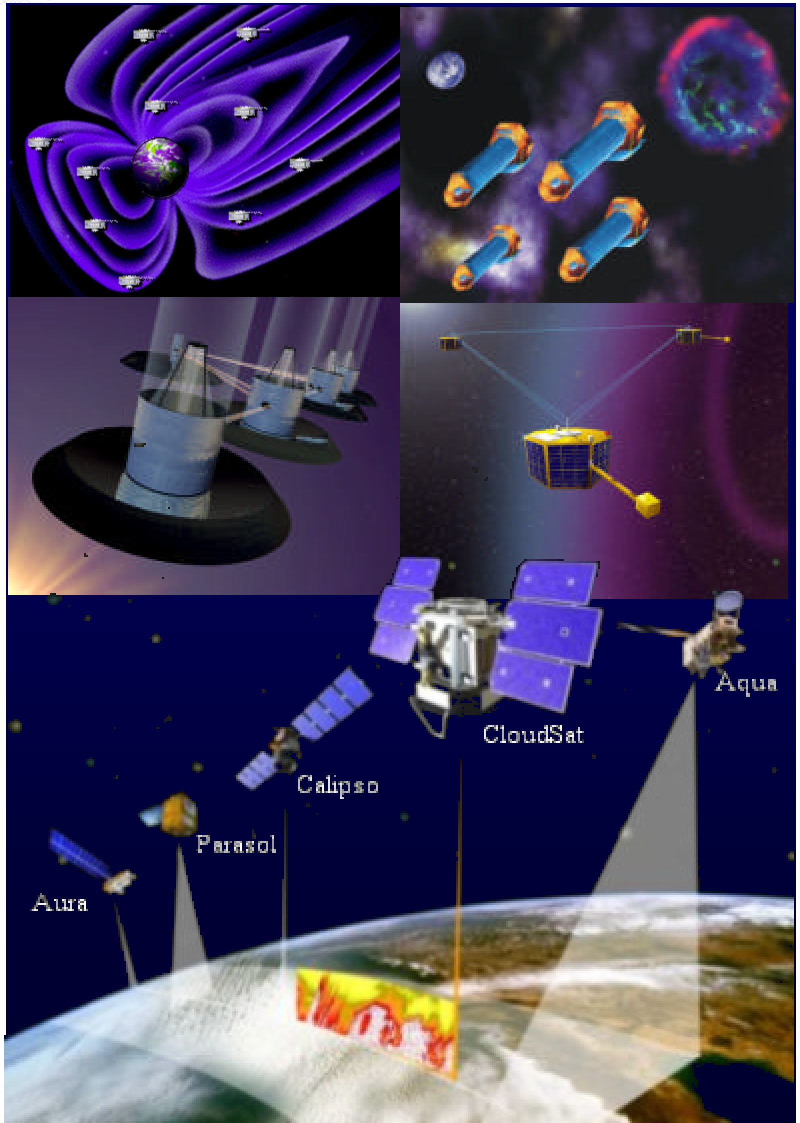
Mission Drivers:

- Operating in unknown and harsh environments for extended periods of time.
- Eliminate the need for large ground support team to monitor craft.
- Real-time response during critical mission phases.

Key Technical Challenges:

- Hybrid diagnosis -- Combining detailed diagnostic agents with system-level reasoners.
- Real-time decision making
- Probabilistic reasoning – Efficient inference algorithms that leverage an explicit representation of uncertainty.
- Model specification process
  - Knowledge engineering
  - Machine learning/system identification.
- Detecting subtle degradations over time.

Agent Architectures and Distributed Autonomy



Mission Autonomy Challenges

- Low-cost, scalable ground operations for multiple-asset missions.
- Collective planning and scheduling to enable coordinated operations
- Low-bandwidth approaches to onboard coordination.
- Ad hoc networking of existing satellites
- Collective fault detection, isolation and recovery.